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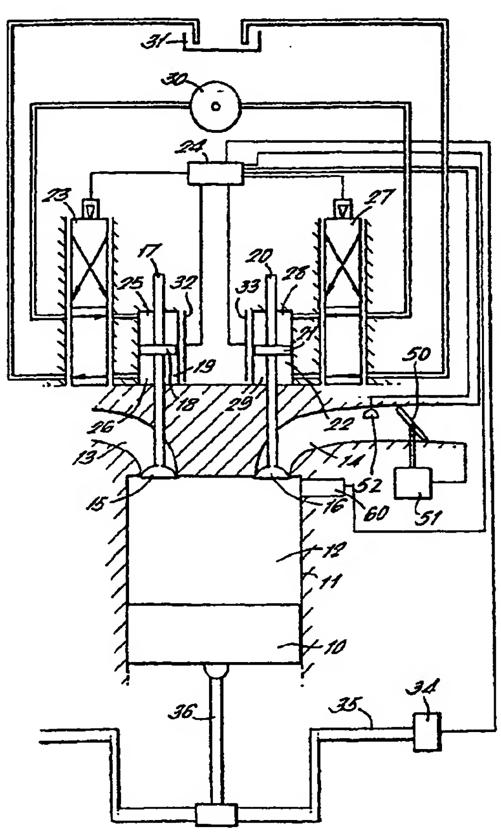

(57) Abstract: The present invention relates to a method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process, in which flow of air into and flow of combusted gases from at least one combustion chamber (12) is regulated by valve means (15, 16) in order to ensure that the air is mixed with the combusted gases so as to generate conditions in the combustion chamber suitable for operation of an auto-ignition process. In the engine of the invention fuel is delivered directly into the combustion chamber (12), e.g. by an injector (60), separately and independently from the air whose flow is regulated by the valve means (15, 16).

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A DIRECT INJECTION FOUR STROKE ENGINE WITH AUTO-IGNITION

The present invention relates to a four-stroke internal combustion engine.

Increasingly stringent fuel economy and emissions targets are being imposed by government legislation. These and consumer pressures continually force the automotive industry to investigate new ways of improving the combustion process of the internal combustion engine.

Once such approach is the auto-ignition (AI) process. In this process a mixture of combusted gases, air and fuel is created which ignites without the need for a spark during compression. The process is sometimes called self-ignition. It is a controlled process and thus differs from the undesirable pre-ignition which has been known in some spark-ignition engines. It differs from compression ignition in diesel engines because in a diesel engine the diesel fuel ignites immediately on injection into a pre-compressed high temperature charge of air, whereas in the auto-ignition process the fuel and air and combusted gases are mixed together prior to combustion. Use of the auto-ignition process in two-stroke engines is well known. The present invention relates to the application of this process to a four-stroke internal combustion engine.

In US 6082342 there is described a four-stroke internal combustion engine which has an electro-hydraulically controlled exhaust valve controlling flow of combusted gases from a variable volume combustion chamber defined by a piston

reciprocating in a cylinder, the exhaust valve being closed before the end of the exhaust stroke to keep in the combustion chamber combusted gases for mixing with subsequently introduced fuel/air charge. The exhaust valve is operated to trap combusted gases for mixing with a fuel/air charge to create conditions in the combustion chamber suitable for operation of an auto-ignition process. US 6082342 also describes an engine with mechanically cam-activated exhaust valves with an opening period which is elongated with respect to the opening period of a conventional spark ignition combustion engine so that there is an overlap period when both the air inlet valve and an exhaust valve of a combustion chamber are simultaneously open during an induction stroke so that both a fuel/air charge and combusted gases are drawn into the combustion chamber. Again this is done to promote conditions in the combustion chamber suitable for auto-ignition. In all embodiments described in US 6082342 fuel and are delivered together to the combustion chamber under the control of an inlet valve or valves.

The present invention provides a method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process and in which flow of air into and flow of combusted gases from at least one combustion chamber is regulated by valve means in order to ensure that the air is mixed with the combusted gases so as to generate conditions in the combustion chamber suitable for operation of an auto-ignition process, characterised in that fuel is delivered directly into the said combustion chamber separately and independently from the air whose flow is regulated by the valve means.

The combination of gasoline direct injection and auto-ignition gives benefits of improved fuel economy and reduced emissions.

Preferred embodiments of the present invention will be described with reference to the following figures:

Figure 1 is a schematic illustration of a first embodiment of single cylinder four-stroke engine according to the present invention;

Figures 2a and 2b are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to a conventional method of operation;

Figures 3a, 3b and 3c are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to the method of the present invention, in a first regime;

Figures 4a, 4b and 4c are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to the present invention in a second regime;

Figures 5a, 5b and 5c are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to the method of the present invention, in a third regime;

Figure 6 is a schematic illustration of a second embodiment of single cylinder four-stroke engine according to the present invention;

Figure 7 is a schematic illustration of a third embodiment of single cylinder four-stroke engine according to the present invention;

Figures 8a, 8b and 8c are valve timing diagrams

for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine having two exhaust valves operating according to a variation of the third regime;

Figures 9a and 9b are valve timing diagrams for the exhaust and inlet valves of a single cylinder four-stroke internal combustion engine operating according to the method of the present invention, in a fourth regime;

Figure 10 is a schematic illustration of a fourth embodiment of single cylinder four-stroke engine according to the present invention; and

Figure 11 is a schematic illustration of a fifth engine according to the present invention.

For simplicity, the detailed description following will address the method of the present invention in its application to a single cylinder four-stroke internal combustion engine, although it should be appreciated that the present invention is equally applicable to a multicylinder four-stroke internal combustion engine.

A schematic representation of a first embodiment of a single-cylinder four stroke internal combustion engine is given in Figure 1. In the Figure a piston 10 is movable in a cylinder 11 and defines with the cylinder 11 a variable volume combustion chamber 12.

An intake passage 13 supplies air into the combustion chamber 12. The flow of the air into the combustion chamber 12 is controlled by an intake valve 15.

A gasoline direct injector 60, controlled by an electronic controller 24, is used to inject fuel directly into the combustion chamber 12.

Combusted gases can flow from the combustion chamber 12 via an exhaust passage 14 and flow of combusted gases through the exhaust passage 14 is controlled by the exhaust valve 16.

The inlet valve 15 and the exhaust valve 16 are hydraulically actuated. It can be seen in the Figure that the stem 17 of the inlet valve 15 has provided thereon a piston 18 which is movable in a cylinder 19. Similarly, the stem 20 of the exhaust valve 16 has a piston 21 provided thereon which is movable in a cylinder 22.

Flow of hydraulic fluid to the cylinder 19 is controlled by a servo-valve 23. The servo-valve 23 is electrically controlled. This servo-valve 23 is controlled by control signals generated by the electronic controller 24. The servo-valve 23 can control hydraulic fluid to flow into an upper chamber 25 of an arrangement of the piston 18 and the cylinder 19 whilst controlling flow of hydraulic fluid out of a lower chamber 26. The servo-valve 23 can also control flow of hydraulic fluid to and from the cylinder 19 such that hydraulic fluid is delivered to the bottom chamber 26 whilst hydraulic fluid is expelled from the upper chamber 25. The fluid supplied to and expelled from the cylinder 19 is metered, so as to control exactly the position and/or velocity of the inlet valve 15.

In a similar fashion, a servo-valve 27 is

provided to control flow of hydraulic fluid to and from the cylinder 22. The servo-valve 27 is controlled electrically by the electronic controller 24. The servo-valve 27 can operate to supply hydraulic fluid under pressure to an upper chamber 28 of a cylinder 22 whilst allowing hydraulic fluid to be expelled from the lower chamber 29 of the cylinder 22. Conversely, the servo-valve 27 can allow pressurised hydraulic fluid to be supplied to the lower chamber 29 whilst allowing hydraulic fluid to be expelled from the upper chamber 28. The servo-valve 27 meters the flow of hydraulic fluid to and from the cylinder 22 in order to control the position and/or the velocity of the exhaust valve 16.

Both of the servo-valves 23 and 27 are connected to a pump 30 and a sump 31. Hydraulic fluid under pressure is supplied by the pump 30 and when hydraulic fluid is expelled from either or both of the cylinders 19 and 22 it is expelled to the sump 31. The pump 30 will in practice draw fluid from the sump 31 to pressurise the fluid and then supply the pressurised fluid to the servo-valves 23 and 27.

The electronic controller 24 will control the movement of the inlet valve 15 and exhaust valve 16 having regard to the position of the inlet and exhaust valves 15 and 16 as measured by two position transducers 32 and 33. The controller 24 will also have regard to the position of the engine, which will be measured by a rotation sensor 34 which is connected to a crank shaft 35 of the internal combustion engine, the crank shaft 35 being connected by a connecting rod 36 to the piston 10 reciprocal in the cylinder 11.

The engine of the present invention has an hydraulically controlled valve train with an electronic controller 24 which is programmable and hydraulically controls the opening and closing of both the inlet 15 and exhaust 16 valves. This enables control of the motion of the inlet 15 and exhaust 16 valves and in particular the time (in terms of the engine cycle) when the inlet 15 and exhaust 16 valves open and the duration of time for which they are open.

Conventional four-stroke internal combustion engines have cam shafts which drive the inlet and exhaust valves. The cam shafts have cam profiles which are designed to maximum the gas flow through the engine. Such engines rely on a spark plug to ignite the mixture. They also rely on an intake throttle to reduce gas flow and therefore control the power output of the engine.

In an engine according to the first embodiment of the present invention the movement of the inlet 15 and exhaust 16 valves will be used for total gas flow management, controlling both the amount of air flowing into and out of the combustion chamber 12 during each stroke of the engine and also controlling the internal mixing process between the different gas species inside the combustion chamber 12 and also to an extent inside the inlet passage 13 and exhaust passage 14. The valve motion in the internal combustion engine according to the present invention will be very different from the motion of inlet and exhaust valves controlled by a conventional mechanical cam shaft. The valve motion will comprise different duration valve opening periods, different height lifts and a different number of lifts in each stroke. This will

allow the engine valves 15 and 16 to control gas flow, engine load/power and also the timing of combustion within the engine. There will therefore be a reduced need for a throttle system and a reduced need for a spark plug. It may be that a spark plug is used only on start up of the engine or at low temperatures.

The auto-ignition process is already well-known in two-stroke engines. It provides improved fuel consumption, a lower engine emission (principally lower hydrocarbons and carbon monoxide) and improved combustion stability. The two-stroke engine is an ideal engine for auto-ignition because auto-ignition relies upon the retention of some exhaust gas in the combustion chamber and a two-stroke engine can easily facilitate this, because the process of scavenging exhaust gases can be controlled to leave the required residual amount of exhaust gas in the mixture of fuel and air ready for combustion. Auto-ignition can provide reproducible combustion time after time.

Control of the motion of the inlet valve 15 and exhaust valve 16 in accordance with the present invention is illustrated with reference to Figures 3a, 3b, 3c, 4a, 4b,4c, 5a,5b, 5c, 8a, 8b, 8c and 9a, 9b with Figures 2a and 2b giving an operating regime of normal camshaft operated valves for comparison.

Figures 2a and 2b show typical valve motion in a standard four-stroke internal combustion engine. The zero degree position is the beginning of the expansion stroke of the engine. Figure 2a shows that the exhaust valve opens in the expansion stroke roughly 30 degrees before bottom dead centre and Figure 2b shows that the exhaust valve remains open throughout the exhaust

stroke to close at the beginning of the induction stroke at roughly 10 degrees after top dead centre. Figure 2a also shows that the inlet valve begins to open at the end of the exhaust stroke about 10 degrees before top dead centre, remains open throughout the induction stroke and Figure 2b shows that the inlet valve closes in the beginning of the compression stroke at about 45 degrees after bottom dead centre.

Figures 3a and 3b graphically illustrate in a first format exhaust and inlet valve motion according to a first operating regime of the present invention. Figure 3c illustrates the same valve motion in a second graphical format. The hydraulically operated exhaust valve 16 begins to open at approximately 10 to 15 degrees before bottom dead centre in the expansion stroke, and closes earlier, closing during the exhaust stroke in a range of 90 to 45 degrees before top dead centre. The inlet valve is opened later in the engine cycle than in an ordinary engine, being opened in a range of 45 to 90 degrees after top dead centre in the induction stroke. The inlet valve 15 is then closed roughly 30 degrees after bottom dead centre in the compression stroke.

The engine operated according to the cycle illustrated in Figures 3a, 3b and 3c is operated to specifically control the flow of gases to achieve auto-ignition of the fuel/air charge in the four-stroke engine. The exhaust valve is controlled to close early during the exhaust stroke and thereby trap a significant volume of exhaust gas inside the combustion chamber 12 for the purpose of generating auto-ignition at the end of the next compression stroke or beginning of the next expansion stroke. When

the inlet valve 15 is opened in the induction stroke as shown in Figure 3 the inlet valve 15 allows a charge of air to enter the combustion chamber 12 and mix with the combusted gases trapped in the immediately preceding exhaust stroke. The mixture of air and combusted gases is subsequently compressed during the compression stroke. The gasoline direct injector 60 will inject fuel directly into the combustion chamber 12, into the mixture of combusted gases and air, either during the induction stroke or during the subsequent compression stroke.

The number of degrees of crankshaft rotation before top dead centre at which the exhaust valve 16 closes is preferably equivalent to the number of degrees after top dead centre at which the inlet valve 15 opens. The reason for this is the trapped combusted gases will be compressed after the closure of the exhaust valve 16 and it is preferred to expand the trapped compressed exhaust gases to the same degree before the inlet valve 16 is opened, so that the pressure in the combustion chamber 12 is not a raised pressure when the inlet valve 16 is opened.

Figures 4a and 4b illustrate exhaust and inlet valve motion according to a second operating regime of the present invention. Figure 4a shows that the exhaust valve 16 opens in a range of 70 to 30 degrees before bottom dead centre in the expansion stroke and Figure 4b shows that the exhaust valve 16 closes in a range of 70 to 90 degrees after top dead centre during the induction stroke. Also, it can be seen in Figure 4b that the inlet valve 15 opens approximately 10 degrees after top dead centre in the induction stroke and closes approximately 45 degrees after bottom dead

centre in the compression stroke. This is also illustrated in Figure 4c.

The regime of Figures 4a, 4b and 4c gives a long period of opening of the exhaust valve 16 and quite a lengthy duration of opening of the inlet valve 15, and gives a period in which both valves are open. This allows a slow and controlled mixing of the inlet charge air and the combusted gases to promote desired chemical and thermal boundary layers between the inlet charge air and the combusted gases compatible with auto-ignition during the compression stroke. It is preferable that when the internal combustion engine is operated according to the method illustrated in Figures 4a, 4b and 4c that a supercharger or turbocharger is used to force air charge into the combustion chamber. Otherwise, the pressure of the remaining combusted gases might impede the introduction of fresh charge air.

The gasoline direct injector 60 will inject fuel directly into the combustion chamber, into the mixture of air and combusted gases, either during the induction stroke or the subsequent compression stroke.

Figures 5a, 5b and 5c illustrate a third operating regime according to the present invention. In this operating regime the exhaust valve 16 is opened twice during each 360 degree rotation of the crankshaft 35. The exhaust valve 16 is opened for the first time during an engine cycle at roughly 30 degrees before bottom dead centre at the end of the expansion stroke (see Figure 5a). The exhaust valve 16 is then closed for the first time at the end of the exhaust stroke and the inlet valve 15 is

simultaneously opened (see Figure 5b). The inlet valve 15 remains open at least for the majority of the induction stroke and closes during a range of 10 degrees before to 10 degrees after the bottom dead centre point of the piston 10 at the end of the induction stroke (see Figure 5b). The exhaust valve 16 is opened for the second time during the same engine cycle at roughly 80 degrees before the piston 10 reaches bottom dead centre at the end of the induction stroke (see Figure 5b). The exhaust valve 16 is closed for the second time during the single engine cycle at roughly 20 degrees of crankshaft rotation past the bottom dead centre portion of the piston 10 at the end of the induction stroke (see Figure 5b).

In the third operating regime the exhaust valve 16 is opened twice during a single engine cycle. During the first period of opening combusted gases are expelled for the combustion chamber to the exhaust passage 14. During the second period of opening previously exhausted combusted gases are drawn back into the combustion chamber from the exhaust passage 14 at the same time as air charge is drawn into the combustion chamber 12 through the inlet passage 13. Thus mixing of combusted gases and fresh charge air is achieved and promotes the correct conditions for auto-ignition. It should be noted that the maximum lift of the exhaust valve 16 is less when opened for the second time in each engine cycle.

The gasoline direct injector 60 will inject fuel directly into the combustion chamber, in to the mixture of air and combusted gases, either during the induction stroke or the subsequent compression stroke.

With an engine operating according to the third operating regime, it is preferred that the flow of exhaust gases through the passage 14 is to some degree throttled or restricted to establish a back pressure behind the exhaust valve 16 which facilitates flow of exhausted gases back into the combustion chamber 12 when the exhaust valve 16 is opened for the second period in the engine cycle.

Figure 6 shows a restrictor 40 present in the exhaust passage 14 to restrict flow of exhaust gases. The restrictor 40 provides an orifice 41 of a cross-section smaller than the cross-section of the exhaust passage 14.

Figure 7 shows a variable throttle 50 which can throttle the flow of exhaust gases to a variable degree. The throttle is a butterfly valve mounted on a spindle and connected to an electric motor 51. The electric motor 51 is controlled by the electronic controller 24. The controller 24 receives a signal from a pressure sensor 52 present in the exhaust passage 14 and controls the electric motor to control the position of the valve 50 to throttle the combusted gases to achieve a desired back pressure behind the exhaust valve 16 when the exhaust valve 16 opens for a second time in an engine cycle. The use of a throttle 50 to provide variable throttling is preferable to provide for different operating conditions with varying engine speeds and loads.

Figures 8a, 8b and 8c shows a variation of the third operating regime suitable for an engine as shown in Figure 12 which has two exhaust valves 16 and 116 per cylinder, each controlled by a separate actuator (21, 22; 121,122) controlled each by a servo-valve (27; 127) controlled in turn by the electronic controller 24. Both of the exhaust valves 16 and 116 will lead to a common exhaust passage 14. A first exhaust valve 15 is opened roughly 45 degrees before bottom dead centre at the end of the power stroke. The exhaust valve 16 is then kept open until the end of the exhaust stroke when it is closed and an inlet valve 15 (or a pair of inlet valves) is opened simultaneously. The inlet valve 15 (or valves) is kept open until roughly 10 degrees after the end of the induction stroke. The second exhaust valve 116 is opened during the induction stroke at roughly 80 degrees of crankshaft rotation before the bottom dead centre position of the piston at the end of the induction stroke and closed roughly 30 degrees after the said bottom dead centre position.

The gasoline direct injector 60 will inject fuel into the combustion chamber, into the mixture of air and combusted gases, either during the induction stroke or the subsequent compression stroke.

The maximum lift of the first exhaust valve 16 is higher than the maximum lift of the second exhaust valve 116 and the maximum lift of the second exhaust valve 116 is comparable to the maximum lift of the inlet valve 15 (or valves).

The variation in the third operating regime avoids the need for any single valve to be opened

twice during a single engine cycle.

Restriction or throttling of the exhausted gases flowing through the exhaust passage 14 by a throttle such as variable throttle 50 will be as advantageous in the variation of the third opening regime as in the first described third operating regime.

If there are two inlet valves per cylinder and if the motion of each inlet valve is separately controlled then the inlet valves could be controlled to have differing motions and thereby create swirl of the gases in the combustion chamber to promote mixing and to promote the correct conditions for auto-ignition.

Figures 9a and 9b illustrate a third operating regime according to the present invention. Comparing Figure 2a with Figure 9a, it can be seen that exhaust valve 16 opens slightly earlier(about 45 degrees before bottom dead centre at the end of the expansion stroke) and closes earlier (about 45 degrees before top dead centre in the exhaust stroke) in order to trap a significant volume of combusted gases in the combustion chamber for mixing with the inlet charge of fuel and air. As can be seen in Figure 9b, the inlet valve opening regime comprises a plurality of pulsed short duration (each approximately 10 degrees of crankshaft rotation) openings starting at about 60 degrees after top dead centre in the induction stroke and stopping about 45 degrees after bottom dead centre in the compression stroke.

The operating regimes of Figures 9a and 9b allow a controlled and pulsed entrance of intake charge air

into the combustion chamber 12, which promotes desired chemical and thermal boundary layers between the inlet air charge and the residual combusted gases in order to facilitate auto-ignition during the compression stroke.

The gasoline direct injector 60 will inject fuel directly into the combustion chamber, into the mixture of air and combusted gases, either during the induction stroke or the subsequent compression stroke.

With each operating regime of each engine described above there are at least two methods of operating the direct injector 10. In a first "homogeneous" mode, the fuel would be injected into the combustion chamber 12 early in the induction stroke to creates a homogeneous fuel/air charge very similar in nature to that resulting from delivery of fuel/air charge through an inlet passage. In a preferred second "stratified" mode, the injection of fuel would take place quite late in the induction stroke, creating a bolus of fuel, which bolus would be provided in a precise location in the combustion chamber 12, the location chosen such that the bolus would be surrounded by a mixture of combusted gases and air ideal for the promotion of auto-ignition.

The combination of direct injection and auto-ignition processes will give benefits of improved fuel economy and reduced emissions.

The engine of Figure 1 could itself be beneficially modified by the use of a piston 10 with an asymmetric crown as illustrated in Figure 10. The

piston 10 has a recess 61 in the crown, which defines a region in which the mixture of air and exhaust gas is concentrated prior to the injection of fuel by the injector 60.

The injector 60 could inject LPG, diesel (in a spray rather than a jet as in a normal diesel engine) or natural gas instead of gasoline. The injector 60 could be an air-assist injector.

As mentioned above, whilst the simple engine shown above does not have a spark plug, it may prove necessary to use a spark plug to complement the auto-ignition process, particularly in start-up conditions. It may also prove desirable to run the engine with auto-ignition in part-load/low speed conditions and with spark ignition in full load/high speed conditions.

Whilst the inlet valve 15 and exhaust valve 16 in the above embodiments are both hydraulically actuated, they could be valves actuated purely electrically or by electromagnetic forces.

It has been found that an engine operating according to the operating regimes described above does not need heating of the fresh air charge before delivery of the charge of the combustion chamber 12. Other engines have found charge pre-heating necessary to promote auto-ignition.

CLAIMS

1. A method of operating a four-stroke internal combustion engine in which combustion is achieved at least partially by an auto-ignition process, in which flow of air into and flow of combusted gases from at least one combustion chamber is regulated by valve means in order to ensure that the air is mixed with the combusted gases so as to generate conditions in the combustion chamber suitable for operation of an auto-ignition process, characterised in that fuel is delivered directly into the said combustion chamber separately and independently from the air whose flow is regulated by the valve means.

2. A method as claimed in claim 1 wherein the delivered fuel is gasoline and a gasoline direct injector is used to deliver the gasoline fuel to the combustion chamber.

3. A method as claimed in claim 1 or claim 2 wherein the fuel is delivered to the combustion chamber in an early part of the induction stroke so that the fuel mixes with the air and the combusted gases to form a substantially homogeneous mixture prior to auto-ignition.

4. A method as claimed in claim 1 or claim 2 wherein the fuel is delivered to the combustion chamber at the end of the induction stroke or at the beginning of the compression stroke only after the valve means has stopped flow of air into the combustion chamber.

5. A method as claimed in claim 1 or claim 2

wherein:

when the engine is operating in a first range of engine speeds and loads the fuel is delivered to the combustion chamber in an early part of the induction stroke so that the fuel mixes with the air and the combusted gases to form a substantially homogeneous mixture prior to auto-ignition; and

when the engine is operating in a second range of engine speeds and loads the fuel is delivered to the combustion chamber at the end of the induction stroke or at the beginning of the compression stroke only after the valve means has stopped flow of air into the combustion chamber.

6. A method as claimed in any one of claims 1,2 or 4 wherein the fuel when delivered to the combustion chamber forms a bolus and the fuel is delivered in such a way that the bolus is located in a region of the combustion chamber where the mixture of fuel, air and combusted gases is suited to promote auto-ignition.

7. A method as claimed in any one of the preceding claims wherein the combustion chamber is a variable volume chamber defined in a cylinder by a piston reciprocating in the cylinder and wherein the opening and closing of the valve means is controlled by an electronic processor which operates according to a programme of instructions and which receives an input signal indicative of the position of the piston reciprocating in the cylinder.

8. A method as claimed in claim 7 wherein the fuel,air and combusted gases are concentrated in a selected area of the combustion chamber prior to auto-

ignition by the use of a piston with a shaped crown.

9. A method as claimed in claim 7 or claim 8 wherein the valve means comprises a hydraulically actuated exhaust valve and a hydraulically actuated inlet valve, both controlled by the electronic processor.

10. A method as claimed in claim 9 wherein the hydraulically actuated inlet valve is closed prior to the delivery of the fuel into the combustion chamber.

11. A method as claimed in claim 10 wherein the hydraulically actuated inlet valve is closed during the intake stroke.

12. A method as claimed in any one of claims 9, 10 or 11 wherein the hydraulically actuated valves are poppet valves.

13. A method as claimed in any one of the preceding claims wherein the valve means stops the flow of combusted gases from the combustion chamber before the end of the exhaust stroke in order to trap combusted gases in the combustion chamber to be subsequently mixed with fuel and air introduced into the combustion chamber and thereby to promote the auto-ignition process.

14. A method as claimed in any one of claims 1 to 12 wherein:

the valve means used comprises an inlet valve means controlling flow of air into the combustion chamber from an inlet passage and exhaust valve means controlling exhaust of combusted gases from the combustion chamber to an exhaust passage;

during every complete four stroke cycle the exhaust valve means is opened for two separate periods;

the exhaust valve means is opened for a first period to allow combusted gases to be expelled from the combustion chamber; and

the exhaust valve means is opened for a second period to allow combusted gases previously exhausted from the combustion chamber to be drawn back into the combustion chamber.

15. A method as claimed in claim 14 wherein the flow of combusted gases through the exhaust passage is restricted by use of a restrictor in the exhaust passage.

16. A method as claimed in claim 14 wherein the flow of combusted gases through the exhaust passage is throttled by use of a throttle in the exhaust passage and wherein the method comprises controlling the throttle to provide varying degrees of throttling of the flow of combusted gases through the exhaust passage.

17. A method as claimed in any one of claims 14 to 16 wherein the inlet valve means and the exhaust valve means are simultaneously open for at least part of the second period of opening of the exhaust valve means.

18. A method as claimed in any one of claims 14 to 17 wherein the exhaust valve means used comprises at least two independently movable exhaust valves, a first exhaust valve which is opened during the first period of opening of the exhaust valve means and which is closed during the second period of opening of the

exhaust valve means and a second exhaust valve which is closed during the first period of opening of the exhaust valve means and which is open during the second period of opening of the exhaust valve means.

19. A method as claimed in any one of claims 1 to 13 wherein:

the valve means used comprises an inlet valve means which controls flow of air into the combustion chamber from an inlet passage and an exhaust valve means which controls flow of the combusted gases from the combustion chamber to an exhaust passage;

the method involves keeping the previously opened exhaust valve means open past the end of the exhaust stroke for a period at the beginning of the induction stroke whereby combusted gases previously exhausted from the combustion chamber during the exhaust state are drawn back into the combustion chamber from the exhaust passage.

20. A method as claimed in claim 19 comprising the step of keeping both the inlet valve means and the exhaust valve means simultaneously open at the beginning of the induction stroke so that air is drawn into the combustion chamber from the inlet passage at the same time as combusted gases are drawn back into the combustion chamber from the exhaust passage.

21. A method as claimed in claim 19 or claim 20 comprising the step of pressuring the air by supercharging or turbocharging prior to admitting the air or fuel/air mixture into the combustion chamber.

22. A method as claimed in any one of claims 1 to 13 wherein the valve means allows the air charge into the

combustion chamber by way of a plurality of pulsed openings of the valve means in each cycle of the engine.

23. A four-stroke internal combustion engine operated according to a method as claimed in any one of the preceding claims.

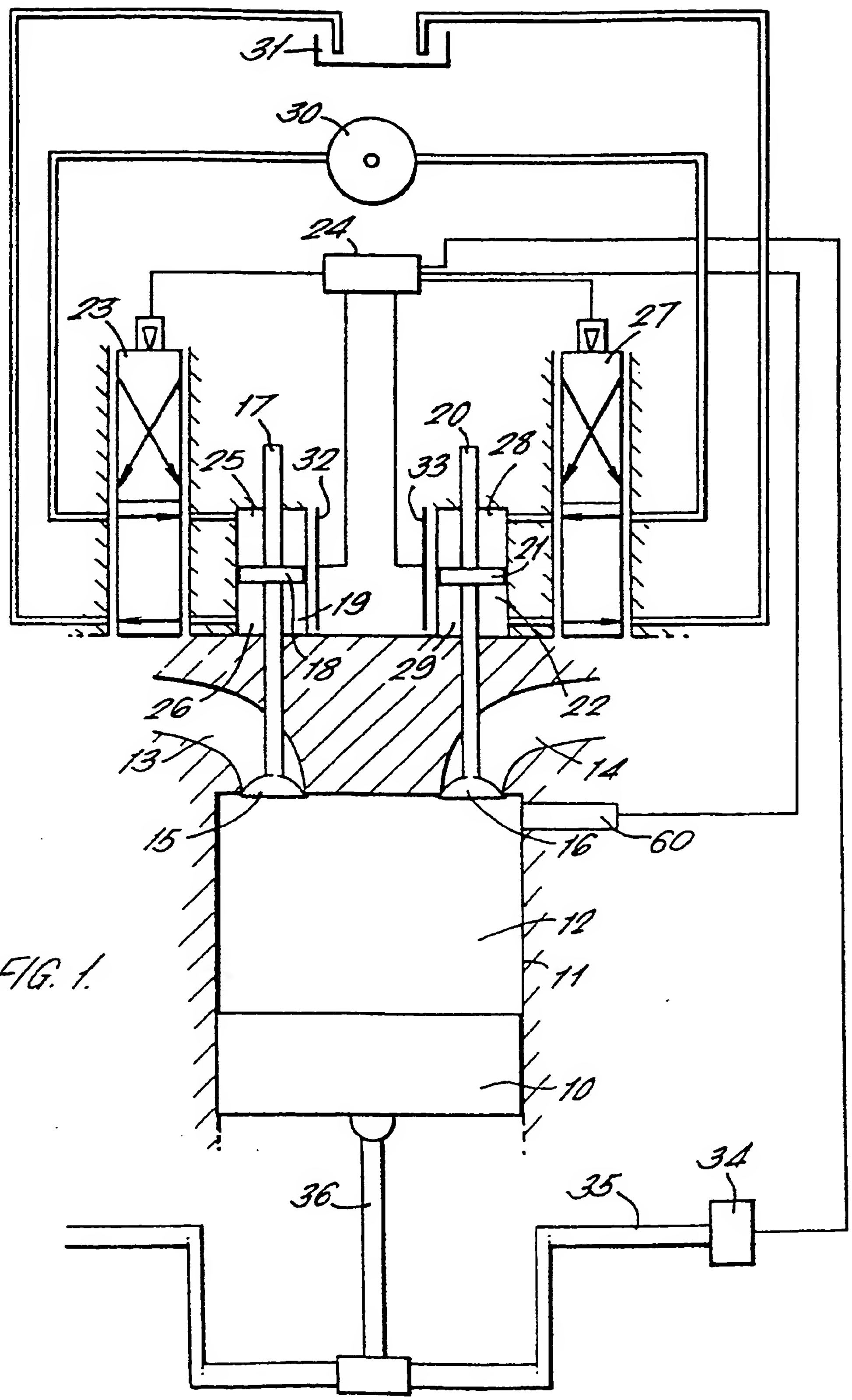
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FIG. 1.

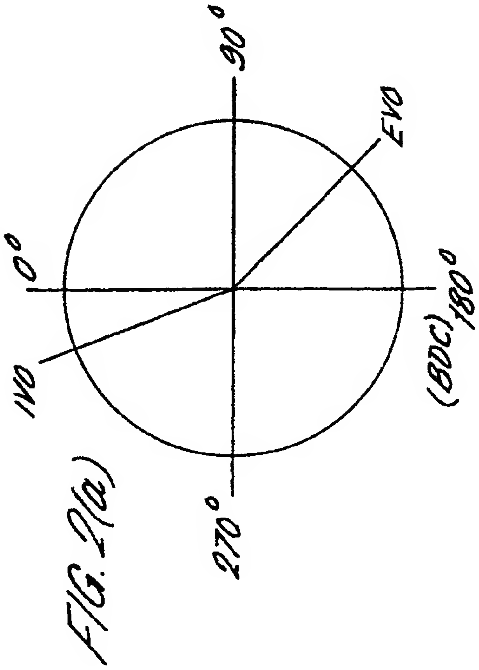

FIG. 2(a)

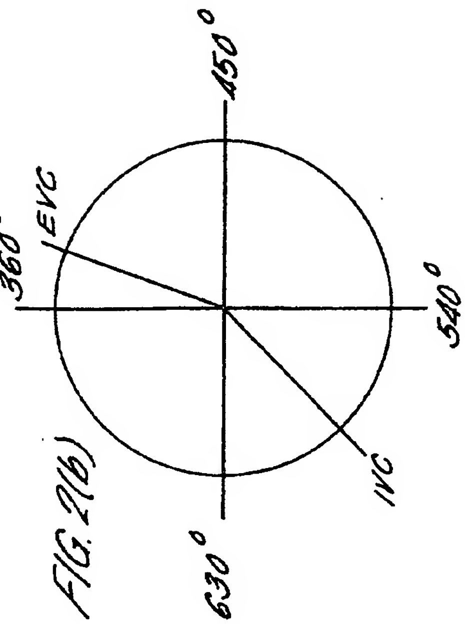

FIG. 2(b)

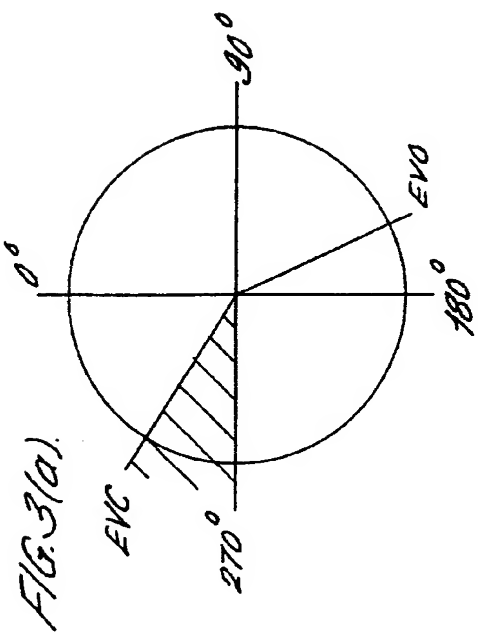

FIG. 3(a).

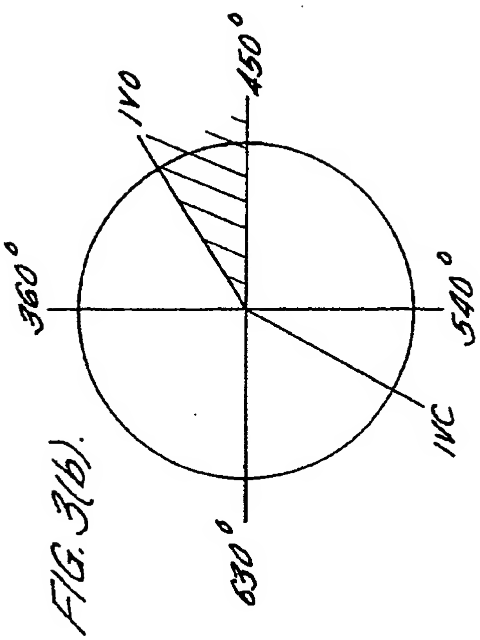

FIG. 3(b).

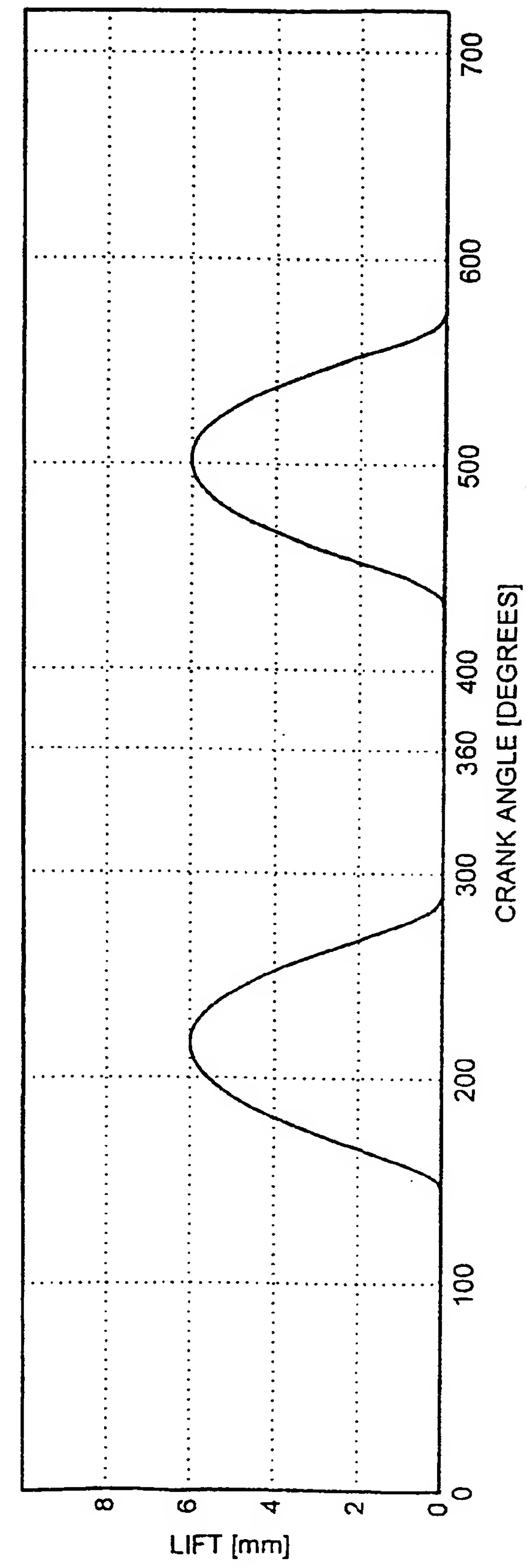
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FIG. 3(c)

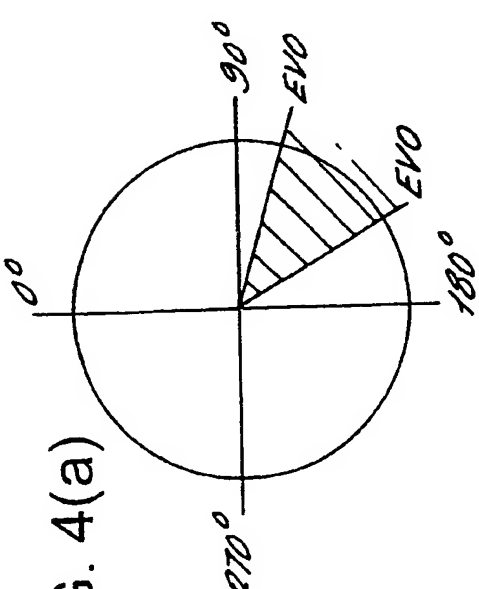

FIG. 4(a)

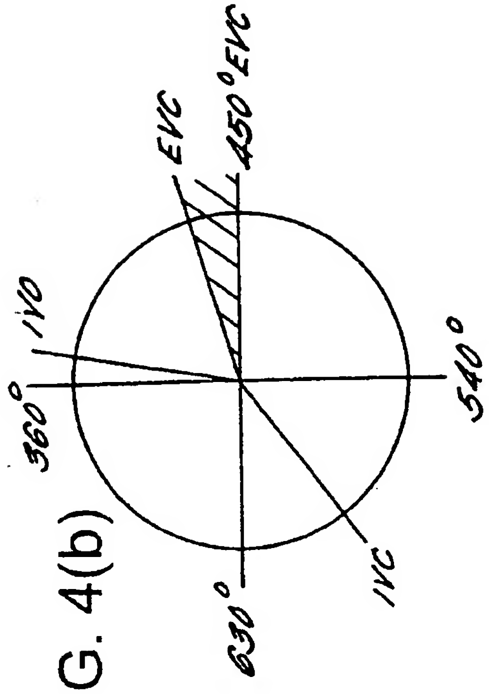

FIG. 4(b)

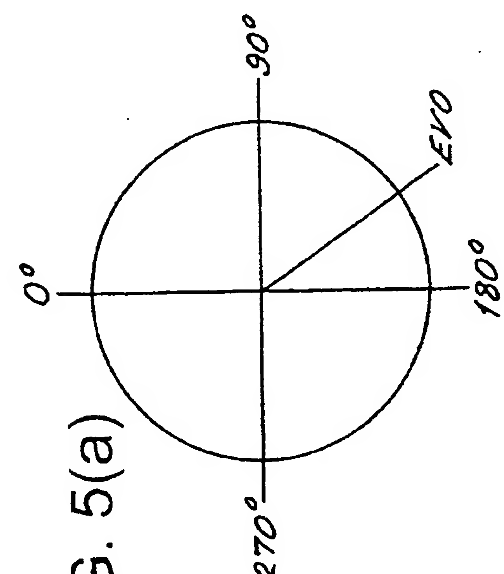

FIG. 5(a)

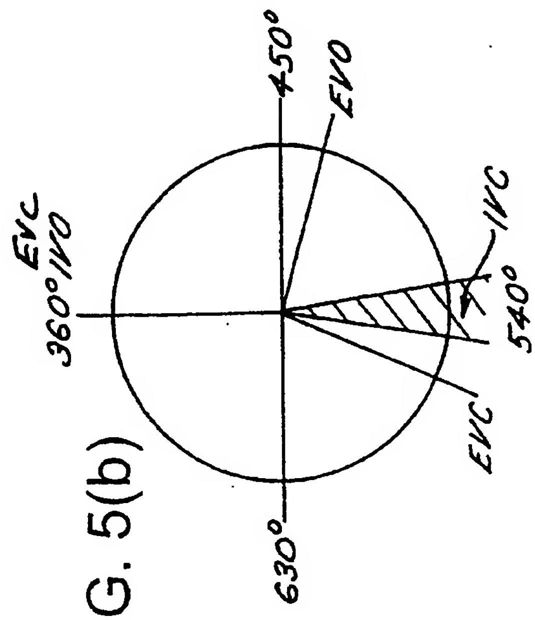

FIG. 5(b)

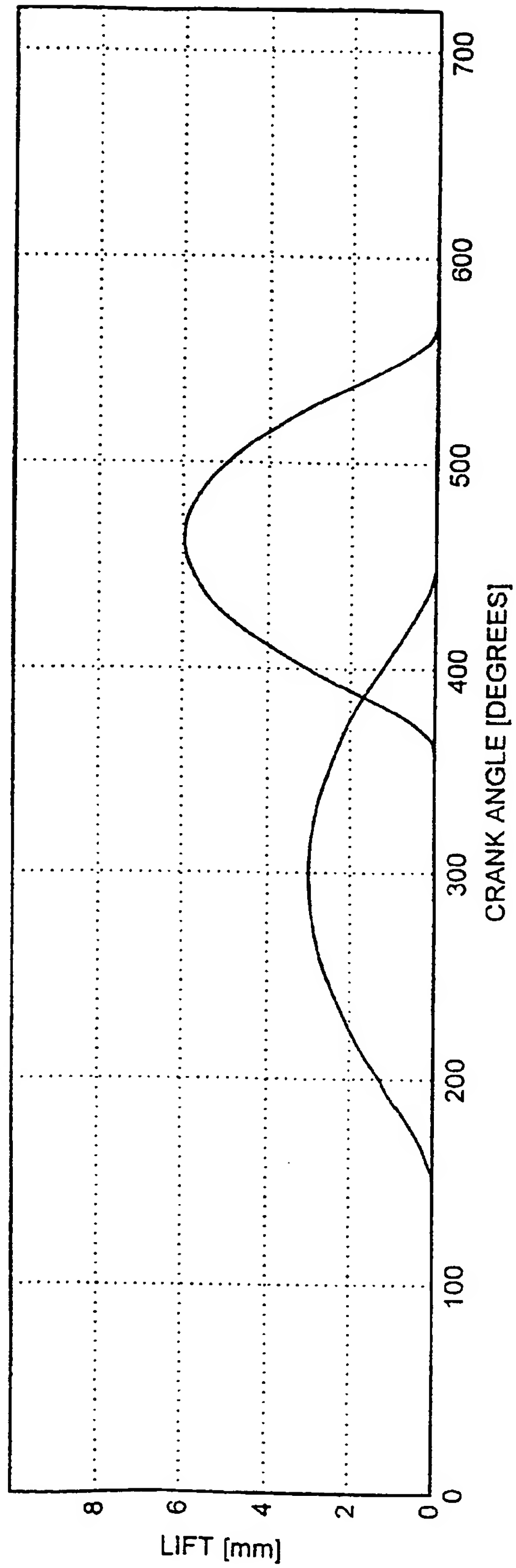
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FIG. 4(c)

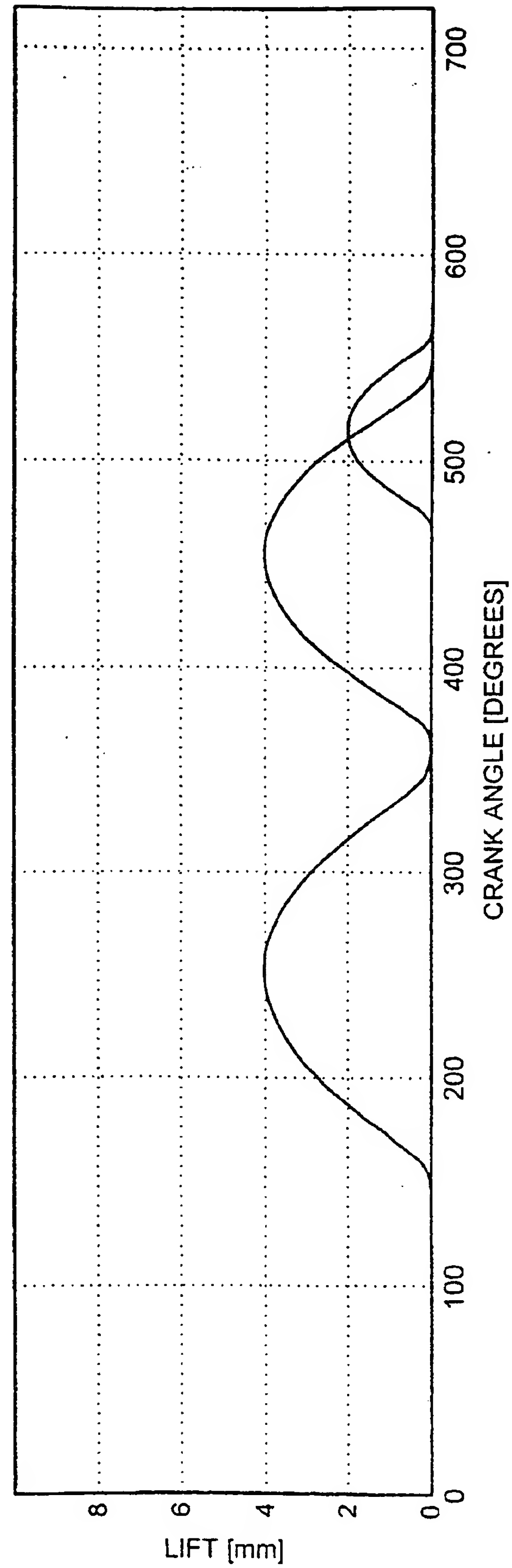
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FIG. 5(c)

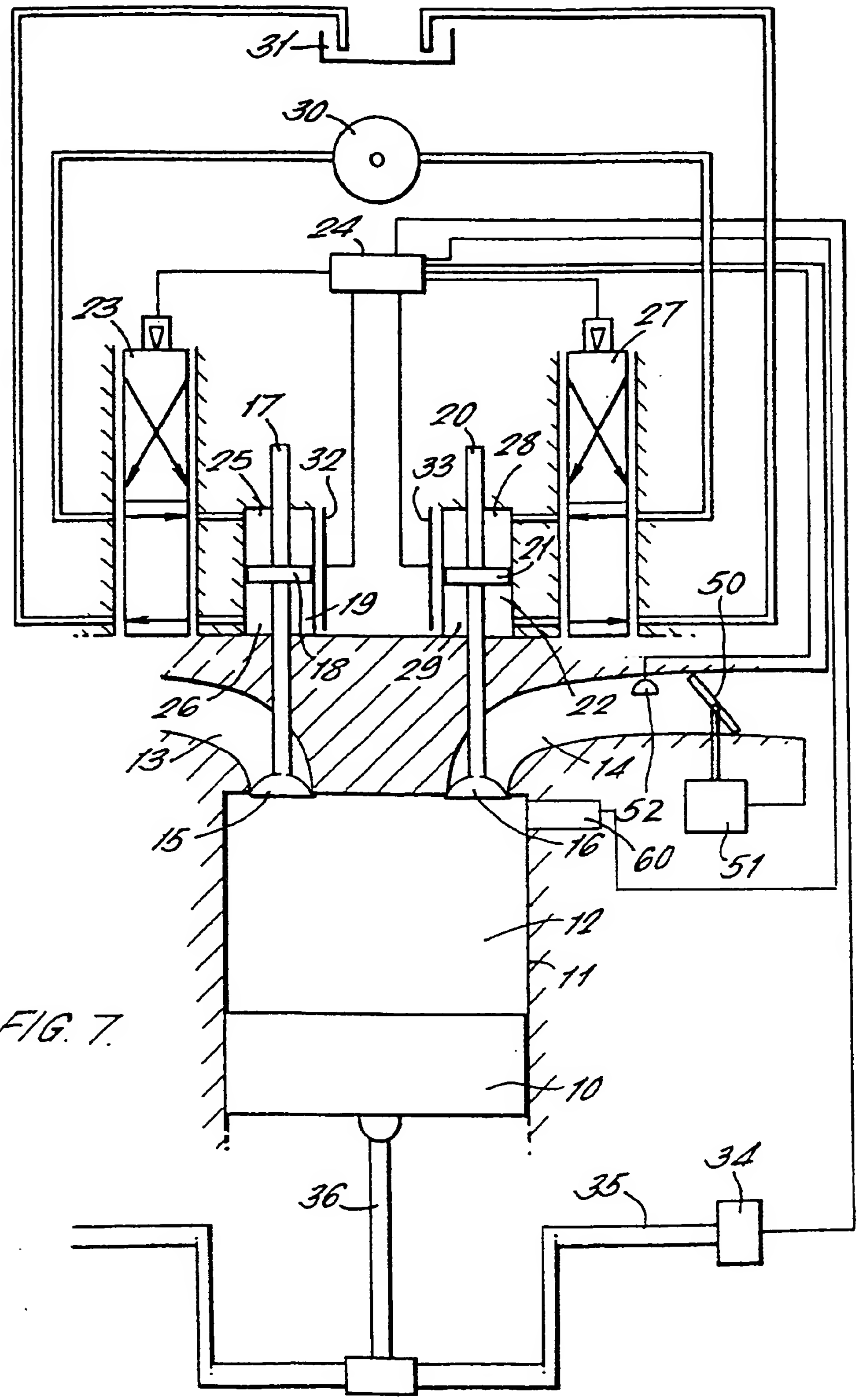
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FIG. 7.

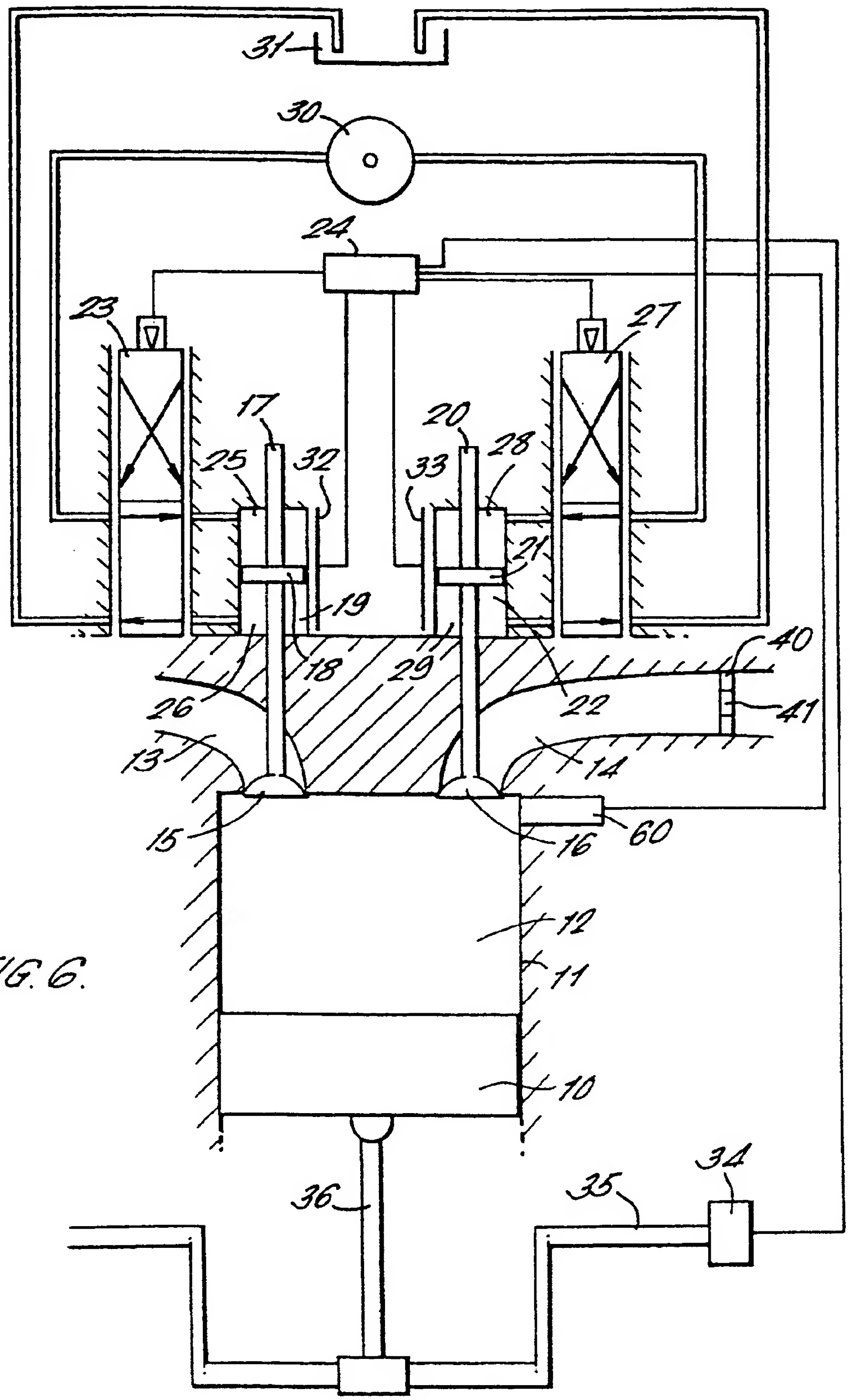
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FIG. 6.

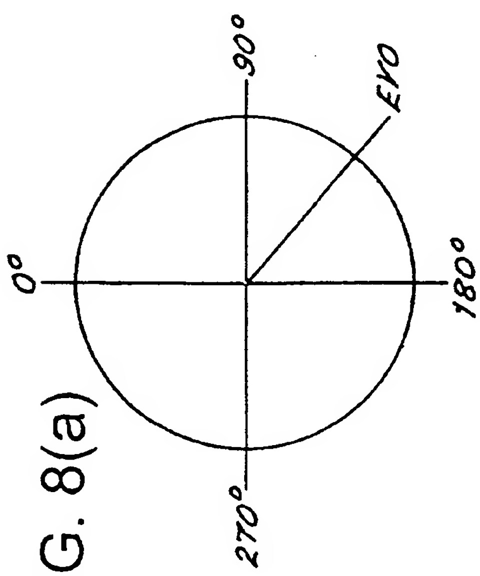

FIG. 8(a)

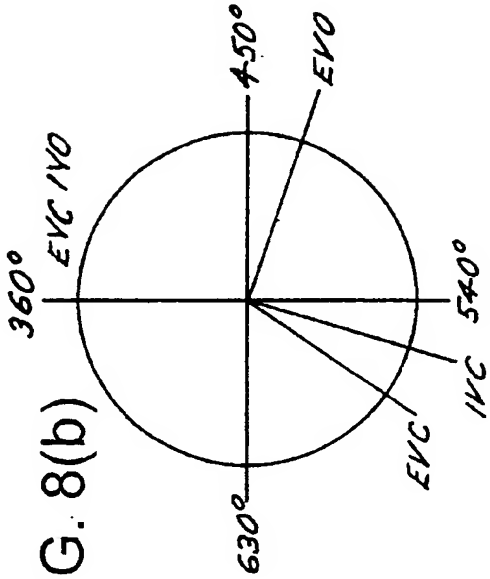

FIG. 8(b)

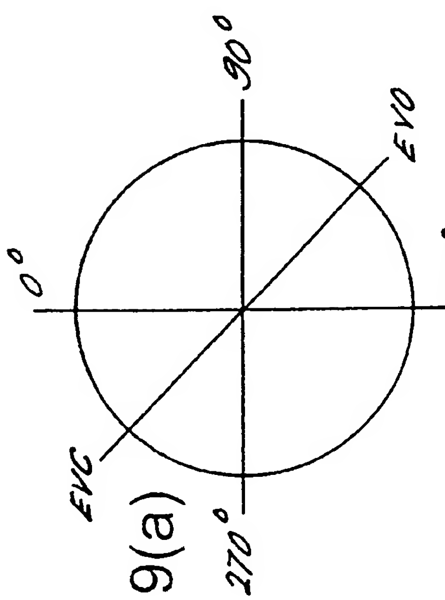

FIG. 9(a)

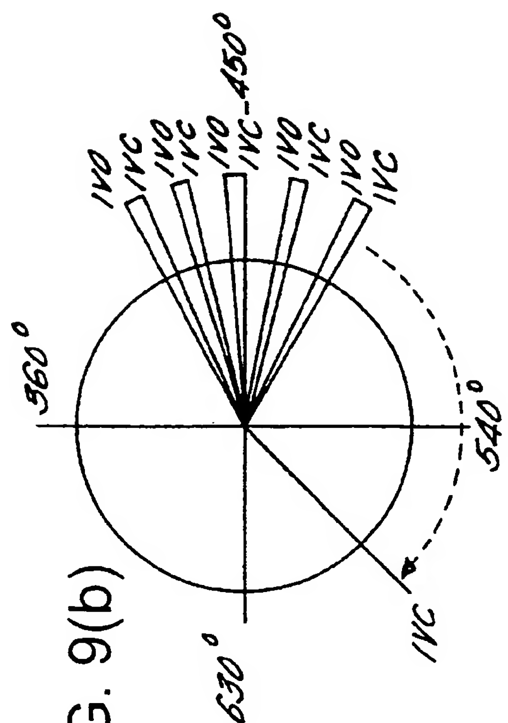

FIG. 9(b)

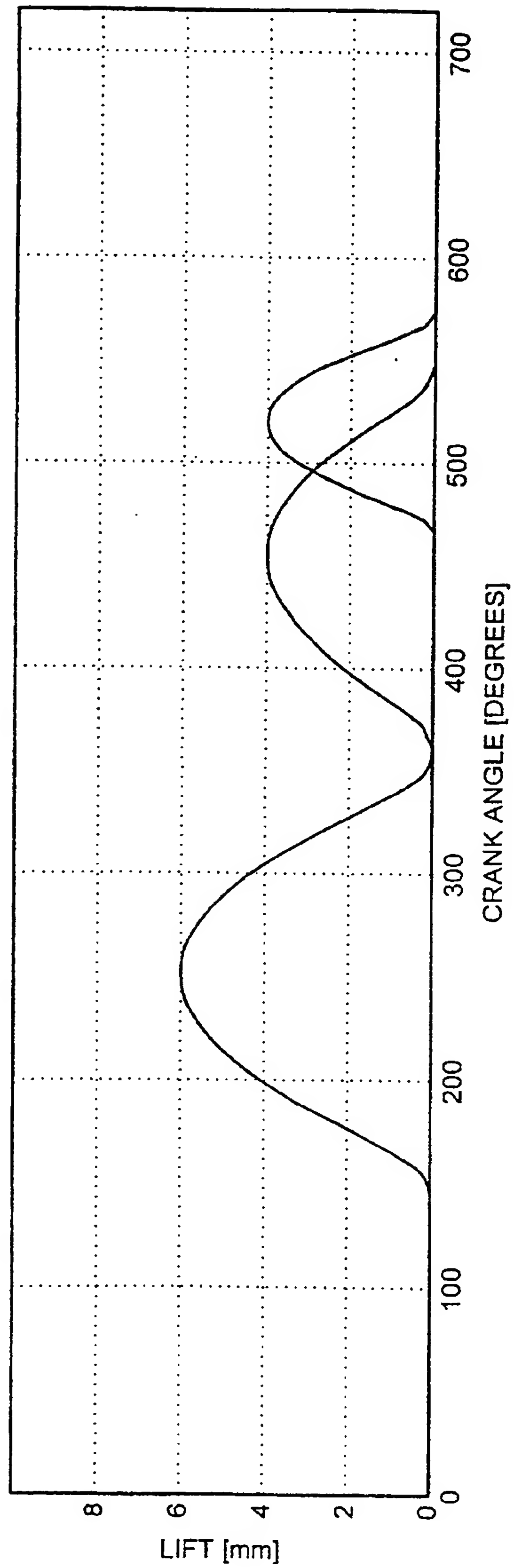
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FIG. 8(c)

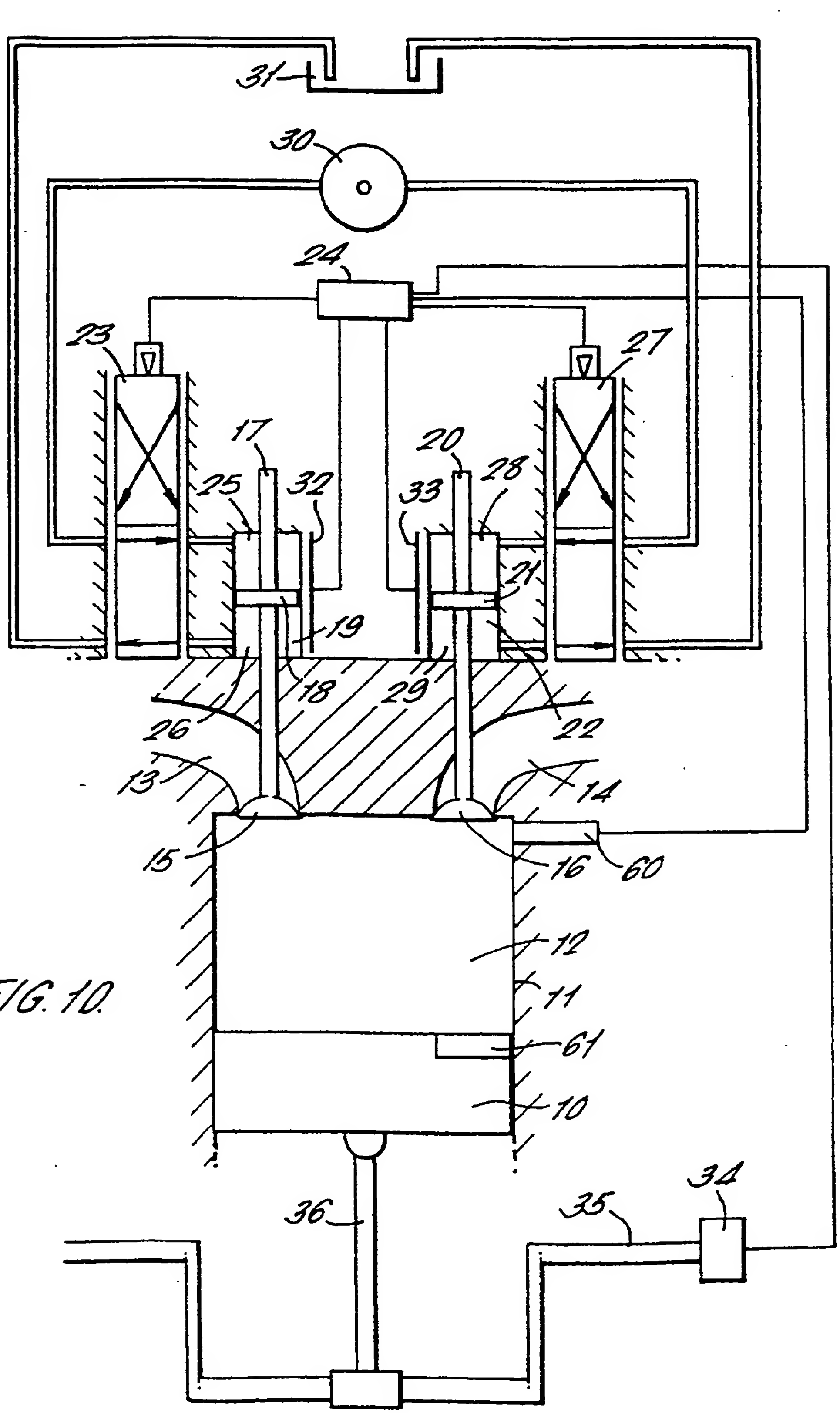
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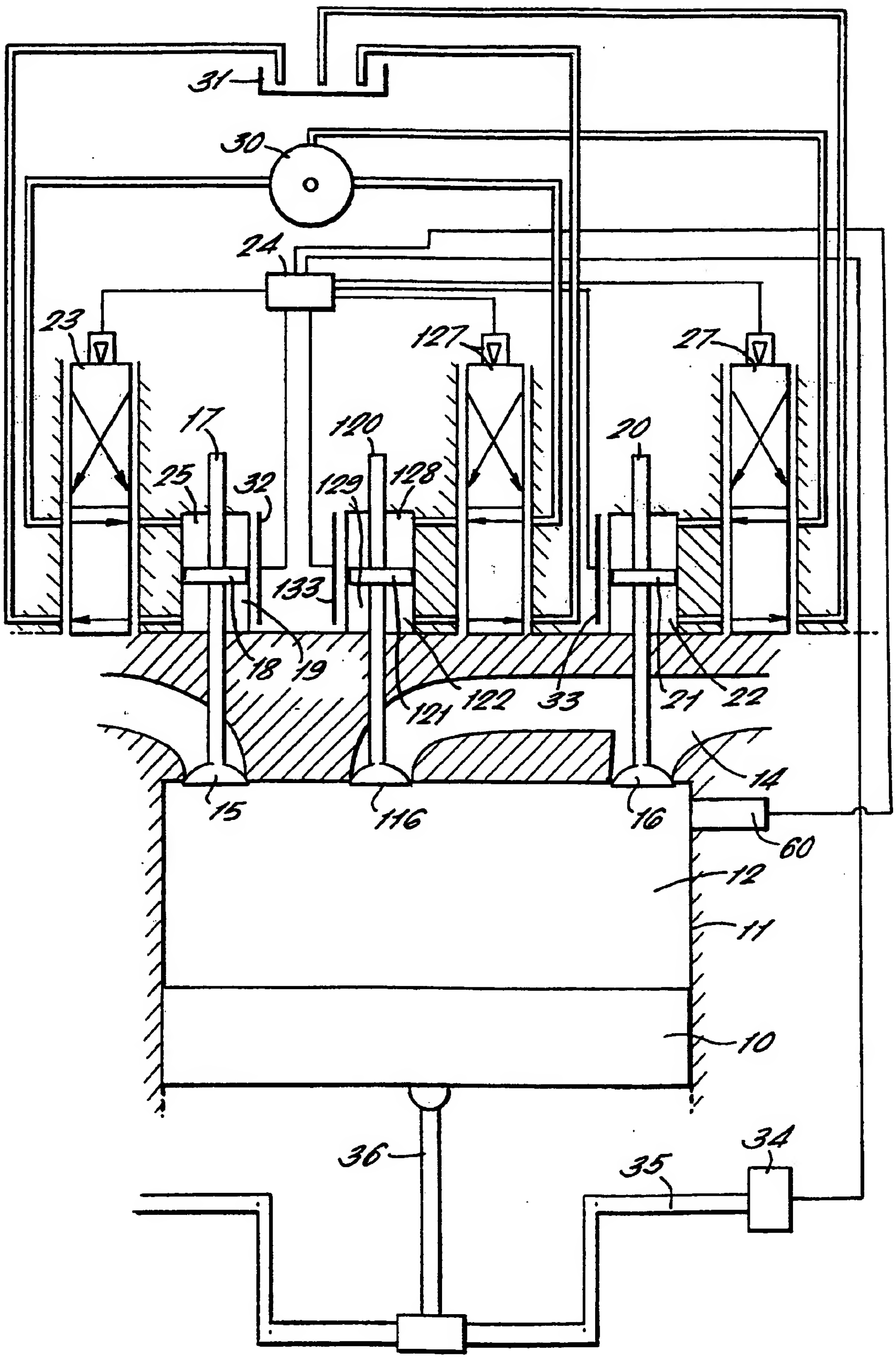
FIG. 10.

FIG. 11.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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 00/04976

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 F02B1/12 F02B11/00 F02B17/00 F02D13/02 F01L9/02
F02M25/07

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 F02B F02D F02M F01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, PAJ, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 99 42718 A (CUMMINS ENGINE CO INC) 26 August 1999 (1999-08-26)	1-3,7, 19-21,23
Y	the whole document	4-6,8-18
A		22

Y	US 5 709 190 A (SUZUKI YUICHI) 20 January 1998 (1998-01-20) abstract; figures 2-4,9-15	4-6,8
A	column 5, line 51 -column 11, line 7	1-3,7, 9-12,23

Y	US 5 862 790 A (DAI WENGANG ET AL) 26 January 1999 (1999-01-26) abstract; figures 1,4-8 column 2, line 37 -column 3, line 6	9-12
A	column 3, line 60 -column 8, line 65	1,7,14, 23

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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27 March 2001	03/04/2001

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Döring, M

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	EP 0 761 950 A (TOYOTA JIDOSHA KABUSHIKI KAISHA) 12 March 1997 (1997-03-12)	13
A	abstract; claims 1,2; figures 1,3 column 2, line 33 -column 5, line 20 ---	1,23
Y	US 5 809 964 A (MEISTRICK ZDENEK; PITZI VINCENT) 22 September 1998 (1998-09-22) abstract; figures 1,5-9 column 6, line 40 -column 7, line 59 column 11, line 9 -column 13, line 20 column 14, line 45 -column 15, line 54 column 16, line 34 - line 58	14-18
A	column 22, line 37 -column 23, line 20 ---	1,7,9, 11-13, 19-21,23
X	DE 198 18 596 A (DAIMLER CHRYSLER AG) 25 November 1999 (1999-11-25) abstract; claims 1-4,6-9; figures 1-3 column 1, line 3 - line 39 column 2, line 56 -column 3, line 18	1-3,7, 13,23
A	column 3, line 50 -column 6, line 19 ---	4-6, 8-12,15, 16,19-21
X	US 4 722 315 A (PICKEL HANS) 2 February 1988 (1988-02-02) abstract; figures 1-4	1,7,9, 10,12, 13,23
A	column 4, line 18 -column 6, line 55 ---	4,11,16, 21
A	US 4 700 684 A (PISCHINGER FRANZ; KREUTER PETER) 20 October 1987 (1987-10-20) abstract; figures 3,7-9,13,15 column 3, line 27 - line 51 column 4, line 14 -column 5, line 17 column 5, line 28 - line 42 column 5, line 54 - line 59 -----	1,13,23

INTERNATIONAL SEARCH REPORT

Information on patent family members

Intc ional Application No
PCT/GB 00/04976

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9942718 A	26-08-1999	BR 9904839 A	18-07-2000
		CN 1263583 T	16-08-2000
		EP 0983433 A	08-03-2000
		JP 2000513788 T	17-10-2000
		JP 2001020784 A	23-01-2001
US 5709190 A	20-01-1998	JP 9014103 A	14-01-1997
US 5862790 A	26-01-1999	NONE	
EP 0761950 A	12-03-1997	JP 9079056 A	25-03-1997
		DE 69609463 D	31-08-2000
US 5809964 A	22-09-1998	US 5787859 A	04-08-1998
		BR 9805963 A	25-01-2000
		EP 0891484 A	20-01-1999
		JP 2000508740 T	11-07-2000
		WO 9834021 A	06-08-1998
		US 6082328 A	04-07-2000
		US 6012424 A	11-01-2000
DE 19818596 A	25-11-1999	US 6105550 A	22-08-2000
US 4722315 A	02-02-1988	DE 3437330 A	24-04-1986
		CH 667310 A	30-09-1988
		FR 2571781 A	18-04-1986
		GB 2165587 A,B	16-04-1986
		HU 42592 A	28-07-1987
		IT 1185402 B	12-11-1987
		JP 61182430 A	15-08-1986
		KR 9311556 B	11-12-1993
		ZA 8507781 A	25-06-1986
US 4700684 A	20-10-1987	BR 8400487 A	11-09-1984
		DE 3401362 A	09-08-1984
		ES 529400 D	01-10-1984
		ES 8407554 A	16-12-1984
		FR 2541372 A	24-08-1984
		GB 2134596 A,B	15-08-1984
		IT 1177540 B	26-08-1987
		JP 59147838 A	24-08-1984
		SE 454286 B	18-04-1988
		SE 8400534 A	05-08-1984